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FIBER LASER AMPLIFIERS AND OSCILLATORS

KJT, Inc.

Kenneth J. Teegarden

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13. ABSTRACT (Maximum 200 words)

This study reports on the experimental development of a passively modelocked fiber laser. It is based on erbium doped fiber, similar to that used successfully in optical amplifiers. The focus of the work is to retain as much signal processing capability in the fiber medium as possible, and to select essential system components for ruggedness and straightforward field integration. The fiber ring laser here described uses the simplest and most compact configuration reported to date. The measured pulse durations are variable from 15 pico seconds to 1 nano-second and are completely self starting. One self-modulation mechanism proposed and described, is nonlinear polarization evolution. The surprising result is that this nonlinear effect is achieved in fiber at the low pump powers available from a compact diode source. This Kerr type effect generates modelocking in the fiber medium, and is somewhat analogous to the mechanism of operation in self-modelocked Ti:Sapphire lasers. The construction of one of the fiber lasers is based on commercially available components most of which are integrated, allowing the final package size to be less than that of a notebook computer. Further work involves increased pulse stability control for applications in fiber communication systems and possibly fiber sensors.

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A SIMPLE PASSIVELY MODELOCKED FIBER LASER OSCILLATOR

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April 29, 1994

I. Introduction

Various types of mode locked fiber laser oscillators designed to produce short pulses at wavelengths in the 1.55 micron telecommunications window have been developed recently.[1-4] Such oscillators are attractive sources of optical solitons and therefore important in advanced broad band, long haul, optical communications systems where a minimum pulse width must be maintained over long distances. With this application in mind, most mode locked fiber oscillators developed to date have been constructed so as to produce pulses with picosecond widths through the use of specially designed amplifiers and auxiliary components. These oscillators usually required high pump powers and were not self starting. Optical solitons are not, however, critical to short haul, distributed communications and control systems, where even nanosecond wide pulses can be tolerated.[5] On the other hand, because of the parallel nature of such systems, low cost components and minimum power consumption are important considerations.

Mode locked lasers based on erbium doped single mode optical fibers have been the subject of intense study for the past few years. Both passive and active mode-locking techniques have been employed. Some of the first successful passively mode-locked lasers were based on a "figure eight Recently, it has been found that simpler single loop configurations containing a minimum of components can also be used to construct self starting mode locked lasers which produce pulses with picosecond widths.[6-10] This new generation of simple ring fiber lasers are potentially compact rugged sources of stable trains of short pulses for a variety of military and industrial applications.

The mechanism for mode-locking in these simple ring lasers is currently thought to be intensity dependent polarization rotation[7-10]. For this mechanism to operate, a polarizing element in the loop is required. In all systems reported to date either a polarization sensitive isolator or a

linear polarizer has been used for this purpose. In this paper we compare the output of a mode-locked fiber laser employing either a polarization sensitive or polarization insensitive isolator but no polarizer. In both cases stable self starting pulses as short as12.6 ps duration are observed.

The objective of the present work was the development and characterization of a laser oscillator based on commercially available optical components. A novel aspect of the fiber ring laser used in our investigations is the use of a standard erbium doped fiber gain module as the gain element in the loop. To our knowledge this is the first demonstration of the possibility of constructing a mode-locked ring laser from a commercially available gain module. From a practical standpoint it is important to find out if such well engineered and efficient amplifiers, designed to produce high gain over as wide a spectral range as possible near 1.55 microns, can readily be converted to laser oscillators operating in either the CW or pulsed mode. In this report we describe a simple self starting diode pumped mode locked laser oscillator which involves a minimum number of readily available parts.

II. Experimental

The layout of the oscillator is shown in Fig. 1. An erbium doped fiber amplifier was used in a unidirectional ring laser configuration. The output of the amplifier was connected to its input through an all fiber splitter, a polarization controller, and a pigtailed isolator of the Faraday rotator type. These components were fusion spliced together to minimize etalon effects which apparently reduce the bandwidth available for mode locking.[11] Either an amplifier constructed in house or a commercial optical amplifier was used as gain portion of the ring oscillator. The amplifiers constructed in house consisted of a length of erbium doped fiber pumped with a 100 mW diode laser operating at 980 nm (Spectra Diode Labs SDL-6312-H1). An all fiber wavelength multiplexer (WDM) was used to mix the pump radiation with the fed back 1.55 mm output. The diode laser output was collimated with a 20x microscope [illegible] and focused onto the input fiber of the WDM with a 5x object [illegible] as found that this launch system resulted in about 45 mW of pump [illegible] the output of the WDM. Two factors were critical in determining the magnitude of the pump power launched into the doped fiber. One of these was the quality of the end of the fiber onto which the pump power was focused by the second microscope objective. This end had to be carefully cleaved using a commercial cleaver (Fujikura High Precision Fiber

Cleaver). A significant loss in pump power occurred at the splice between the WDM output and the erbium doped fiber due to the mismatch in fiber diameters at this point. The diameter of the core of the fiber at the out put of the WDM was 8.0 µm while the doped fiber core diameter was ~5.0 µm. The measured loss due to mode mismatch at this point in a good splice was about 1.25 db.

Many of the problems described above were eliminated by the use of a commercial fiber amplifier (Corning FiberGain Module model P3-35). In this case a pigtailed pump laser operating at 980 nm, the WDM and doped fiber were all included in the module. These components were integrated in the amplifier design to provide stable high gain at minimum pump powers. While similar results were obtained using both the amplifiers constructed in house and the commercial amplifier, the latter provide the most stable out put at the lowest pump currents and was used to obtain most of the data reported below.

The rest of the ring cavity was constructed from readily available components based on standard single mode telecommunications fiber designed to have minimum dispersion at a wavelength of 1.3 µm. The cavity was therefore dispersive at 1.55 µm. Several different splitting ratios between the output signal and the feedback signal were tried. In the case of the very high gain commercial amplifier, a ratio of 50/50 gave the maximum output power. The amplifiers constructed in house had a lower gain and required that a higher fraction of the output be fed back to give the maximum output power. In this case only 10% of cavity power was extracted, while 90% was fed back.

The isolator and polarization controller were essential to stable operation of the mode locked oscillators. Two types of isolators were used. Both were essentially pig tailed Faraday rotators. The first type was non polarizing (OFR IO-G-IR2). The second included a polarizer and therefore acted as a polarizing element in the cavity (OFR IO-G-IR2).

Both the optical spectrum and the temporal characteristics of the output of the oscillators was examined in order to optimize their performance and determine the physical mechanisms responsible for their behavior. Spectra were obtained with a commercial optical spectrum analyzer (Anritzu MS9001B1). The temporal characteristics were observed using either a fast photodiode amplifier combination (Lasertron QRX-700) and a digitizing signal analyzer (Tektronix DSA 602) or an avalanche

photodiode (Antel AMF-20, Mod. MARG-20) in combination with a digitizing sampling oscilloscope (Tektronix 11801). The first combination featured high sensitivity and rapid response but had a band pass of 500 MHz. The band pass of the second combination was measured to be 7.54 GHz corresponding to a resolution of 133 ps. This is illustrated in Fig. 2., where the response of the system to an 8.0 ps pulse from a mode locked YAG laser operating at 1.3 µm is shown. In addition to the above instruments, a background free optical autocorrelator (INRAD 5-14-AD) was used to detect structure faster than the resolution of the above detection systems.

III. Results

The following results were obtained using an oscillator based on the commercial optical amplifier and a ring cavity constructed as above. As noted earlier, results obtained using amplifiers constructed in house were very similar except for details which could be explained in terms of different cavity lengths or higher launched pump powers.

The optical spectrum and the temporal behavior of the oscillator output were examined as a function of pump power. It was found that at threshold and above, the output always consisted of a CW component and a periodic series of short pulses. No special effort was needed to initiate the short pulse component of the output. An oscillograph trace which illustrates this behavior is shown in Fig. 3. Here the output from the slower detector in combination with the digitizing signal analyzer is shown in real time so that the noise due to the detector amplifier and CW component can be seen in combination with the short pulse structure. It was found that the contrast between the periodic pulses and the noise due to the CW output could be maximized by a careful adjustment of the polarization controller. It was also found that this contrast was best at low pump powers, near the threshold for oscillation. As the pump power was increased, noise due to CW oscillation and sporadic harmonic signals apparently caused by mode beating also increased relative to the periodic structure. The harmonic oscillations occurred in short bursts and temporarily suppressed the short pulse operation.

At certain settings of the polarization controllers the period of the pulses was remarkably stable and independent of pump power, enabling averaging techniques to be used to accurately measure the pulse period and average width. An oscilloscope trace obtained in this way is shown in Fig. 4. In

this case the period of the pulses was 189.2 ns, corresponding to a frequency of 5.285 MHz. At other settings of the polarization controllers the output wave form was more complicated as is illustrated by Fig. 5. Here the width of the pulses increased and a secondary set of pulses spaced between the initial set evolved so that the frequency of the pulse train doubled. As shown in Fig. 6, the average pulse width was measured to be 1.246 ns. using the detection system with a band width of 7.55 GHz.

The period of the output pulses was measured as a function of the length of the oscillator cavity to demonstrate that the pulse train was indeed due to mode locking. The result is shown in Fig.7. This data was obtained by fusion splicing known lengths of standard telecommunications fiber into the feed back loop. It is clear that the pulse period was proportional to the cavity length and that the lengths used in these measurements ranged from 46 m to 56 m. A large fraction of the total cavity length was made up of the erbium doped fiber in the amplifier, which was estimated to be approximately 22 m.

The average output power of the ring laser as a function of launched pump power for three different splitting ratios in the output coupler is shown in Fig. 8. With 70% of the light coupled out, the maximum output power was 18.0 mW for a pump power of no more than 50 mW. This result illustrates the point that the high gain obtainable in the erbium doped fiber permits operation with large output coupling. In fact, the optimum coupling ratio may not have been reached in this investigation and even higher output powers may be possible. The results described below were obtained with 30% of the light coupled out.

The temporal behavior of the laser output is further illustrated by the autocorrelation traces shown in Figs. 9 and 10 for both a polarization sensitive and polarization insensitive isolator These were obtained at a pump power of about 50 mW. Assuming a Gaussian line shape, the data in Fig. 9 yields a pulse width of 17.5 ps, measured at half maximum. The pulse width corresponding to the autocorrelation trace shown in Fig.10 is 12.6 ps. The optical spectrum associated with the autocorrelation trace shown in Fig. 9 is given in Fig. 11. When corrected for instrumental resolution, the full width at half maximum of this spectrum is 0.157 nm. At 1.56 μm, this corresponds to a frequency band width of 19.2 GHz. This result taken with the pulse width obtained from Fig. 4 yields a time bandwidth product of 0.34.

In view of the fact that fiber dispersion is known to produce pulse broadening, it was decided to replace part of the telecommunications fiber used in the loop with fiber in which the point of zero dispersion had been shifted to 1.5 µm. This was done by rewinding of of the polarization controllers with dispersion shifted fiber. An autocorrelation trace of the output of the laser under these circumstances is shown in Fig. 13. The width of the modelocked pulses indicated by this trace is about 3.5 ps., considerably shorter than the width of the pulses shown in Figs.10 and11.

IV. Theoretical Analysis

The appearance of a stable train of short pulses with a period set by the length of the oscillator cavity indicates that some form of self mode locking was occurring in the laser oscillator described above. The presence of structure on a picosecond scale in addition to the relatively broader nanosecond scale pulses is further evidence of mode locking. The calculation presented above indicates that this picosecond structure was band width limited. It is possible that the observed nanosecond pulses contained trains of picosecond pulses which were not resolved by the photodetection system used to obtain the data shown in Fig 6 . This behavior has been observed to occur in other types of erbium doped fiber oscillators.[12] It is worth emphasizing that the self mode locking of this oscillator was self starting. In fact, mode locking seems to be the preferred method of oscillation and persists over the entire range of pump powers investigated. It should also be noted that the pump powers used in this investigation were relatively low compared to those reported in other work.

It is interesting to speculate on the mechanism responsibly for mode locking in the simple system used in this work. In the first place it should be noted that the very long cavity employed here results in a very dense temporal mode structure. For example, a period of 186 ns corresponds to a temporal mode separation of 8.33 MHz. The narrowest optical spectrum observed in this work covered a spectral range of 0.15 nm, which corresponds to a frequency width of 11.5 GHz. This range of frequencies overlaps approximately 1.4x103 longitudinal modes! The band width limited spectral range required for 1.3 ns wide pulses is about 10^{-2} nm or 1.77 GHz. Even this narrow spectral range includes about 200 longitudinal modes. In other words, the small temporal mode separation due to a long cavity permits mode locking to occur over a very small fraction of the available gain curve of the fiber amplifier. This reduces the effect of

dispersion on mode separation and makes a large number of modes with equal separations available for mode locking, and may explain why mode locking occurred so easily in this oscillator.

Further, the conventional theory of mode locking results in the following expression for the number of locked modes, N, for a given pulse width t and period T:

$$N = T/t$$

For the mode locked YAG laser used in this work, T = 4.0 ns while t = 8 ps. This gives N = 500. For the erbium doped fiber oscillator, T = 150 ns and t = 1.5 ns, yielding a value of N = 100. This value is consistent with the spectral line widths reported above.

One mechanism for the observed passive self mode locking in the fiber ring laser is hypothesized to be a nonlinear induced polarization evolution. The functioning is somewhat analogous to the Kerr lens self mode locking which has recently revolutionized femtosecond pulse generation in the near IR with Ti:sapphire lasers[15]. It should be mentioned that such passive self mode locking was actually observed as far back as 1968 in a HeNe gas laser. Because both control and gain bandwidth were lacking, the technique remained dormant and largely forgotten until its almost accidental recent 1989 discovery in a Ti:sapphire crystal. The effect in a crystal is due to a nonlinear intensity dependent index change resulting in self-focusing of the beam in the crystal medium, which is also the gain medium. If one pictures an effective aperture in the system near this induced focus, it is apparent that the system throughput is optimized whenever the lensing takes place. When this effect conforms to the round trip interval of the cavity, pulses providing a concentration of the energy become the favored method of operation and can generate a modelocked train. This type of spatial filtering can be alternatively analyzed in the time domain in terms of induced self-phase modulation. The pulse duration is limited by two primary factors; The gain bandwidth of the lasing medium, and the response time of the nonlinear Kerr effect. In both Ti:sapphire and erbium doped silica, the former exceeds 40 nm and the latter is largely due to electron cloud deformation so that tens of fempto seconds are permitted from both mechanisms. The pulsed behavior may or may not be self-starting and often a modulator or movable mirror is incorporated for control in the former case and initiation in the latter.

This type of spatial lensing effect is of course not operable in single mode fiber, but certain other $\chi 3$ effects can be. One of these is the Kerr optical shutter, which can operate in any medium exhibiting Kerr nonlinearity.[13] Materials such as CS_2 have been successful in bulk crystal applications because of high coefficients, but the method of operation applies equally well to fiber. The single propagating mode in an optical fiber is degenerate and supports two eigenmodes orthogonally polarized. Thus if a high intensity flux (in one polarization here chosen as "x") alters one of the refractive indices, the result is a relative phase change for any propagating signal which has components in both polarization axes. This phase change is intensity dependent with a magnitude determined by the field strength of the pump beam and by the relevant nonlinear coefficient . If one visualizes a linearly polarized signal beam launched so as to have equal components in both axes (i.e. $\theta = 45$ deg from the pump polarization axis), it is clear that any induced relative phase change induced by the pump beam will result in elliptical polarization from the induced retardance. A component is therefore generated which is orthogonal to the original axis of launch. Its intensity is given by the following expressions for transmissivity, T_p and phase shift, $\Delta\Phi$.

$$T_p = \sin^2(\Delta\Phi/2)$$

$$\Delta\Phi = 2pL/\lambda(\Delta n_x - \Delta n_y)$$

where L is the length and Δn_i refers to the respective nonlinear induced index changes along the axes. Any inherent birefringence is here ignored. Clearly, if the phase change due to the relative delay is π or an odd multiple, then the entire incident signal is converted to the orthogonal polarization. A polarizer oriented to block the input signal when no pump signal is present, will then function as an optical gate that passes a signal only when pump light is present. In the preceding description of the Kerr gate, the high power pump pulse is distinguished from the signal (or probe) pulse, and in fact the two need not in general even be at the same wavelength. The effect can be rigorously analyzed as a polarization evolution, but is sometimes loosely referred to in this context as rotation. We note that although residual inherent or mechanically induced birefringence also generates rotation effects, these are not intensity dependent and are nulled or compensated in operation so as to have no active role in gating effects. It should be stressed that incomplete

switching of the polarization only reduces the throughput, but does not preclude shutter operation with high extinction ratio.

For this type of mechanism to operate in a fiber ring laser, the primary difference from the previous description is that the so called pump and probe pulses become one and the same. It can be shown theoretically[14] that such self modulation still takes place and has a peak transmissivity given by the somewhat more involved expression:

$$T_p = \sin\{(\gamma/6)P_0L\cos(2\theta)\}\sin^2(2\theta)$$

$$\gamma = \pi n_2/\lambda A_{eff}$$

Here θ is again the launch angle, P_0 the incident power, with n_2 being the nonlinear index coefficient of the fiber, L its length and A_{eff} the core area. Computations show that although total polarization conversion is not achieved, certain choices of incident polarization orientation angle (q) and incident power can yield as much a 90 % efficiency. Even for single pass operation in the absence of a cavity and laser oscillation, pulse shaping will take place at any value of θ which corresponds to a local maximum of the transmissivity function, because the lower intensity wings will incur relative attenuation. Such effects are enhanced in multi-pass oscillation, resulting in a mechanism which promotes decreasing pulse width in the time domain from each pass of the polarizing gate. Thus an intensity enhanced transmissive state, correlating to a compressed temporal pulse, can become the preferred mode of operation as in the solid state case. Both utilize the Kerr effect somewhat differently.

The operation of the Kerr effect has of course been established in various media and configurations including fiber; however, it is generally induced at high field intensity. What is unusual in these fiber ring experiments, is the extremely low threshold observed for modelocking effects. It needs to be shown theoretically, and confirmed experimentally that the required phase shifts or index changes are consistent with known values for the nonlinear coefficients, as well as the optical power levels observed in the cavities. This is done below for the case of the distinct pump/signal case but would apply analogously to the case where they are identical.

Referring back to eq. 1 and using the following expressions to give the

index changes in terms of the optical field intensity and nonlinear coefficient.

$$\Delta n_x = 2n_2 E_2 \qquad \Delta n_y = 2n_2 b E_2$$

The energy density term (square of the field strength) is related to the propagating optical power and effective fiber core area by:

$$P = E^2 A_{eff}$$

Defining the Kerr coefficient:

$$n_{2b} = 2n_2 (1-b)$$

We take b=1/3 as a good approximation in silica. The solution for P required for a complete polarization switching (a phase shift $\Phi = \pi$) is given from inserting the above results into eq. 2. The result is:

$$P = \lambda A_{eff}/2Ln_{2b}$$

The value of $n_{2b} = 5\times10^{-16}$ cm/W as has been established in referenced work and $A_{eff} = 25$ mm^2 is typical of the silica fiber core of the erbium doped fiber used in the lasers and amplifiers. Taking $\lambda = 1.5$ µm and L = 40 m from the first cavity, the requirement is:

$$P = 10 \text{ watts.}$$

This calculation is for a CW value, whereas in our application the pulsed power value must be used. A sufficiently accurate estimate at this stage, can be based on the assumption that the average laser power (measured on a CW meter) is converted to pulsed power. The peak value is then estimated from the product of the CW value with the ratio of the pulse interval to the pulse width. Taking a few measured combinations from the data:

Period T = 400 ns, Width τ = 1 ns, P_{cw} = 4 mw
yields P = 1.6 watts

T = 400 ns, τ = 25 ps, P_{cw} = 20 mw

$$\text{yields} \quad P = 3.2 \text{ watts}$$

It is clear that the intensities can indeed be in the correct order of magnitude. It is typical in fiber applications that the extremely small area core confinement and long interaction length compared with bulk applications, compensate (as shown directly in eq. 5) for the relatively low nonlinear coefficients of the usual fiber core materials. Again, incomplete switching as would be obtained from less peak pulse power, will still exhibit the same mechanism but with some loss per pass. Such losses however can be compensated by the gain provided in the lasing cavity by the pump laser energy. A solution of the rate equations would relate this to the overall energy conversion efficiency, which is at this stage not of primary interest.

The other observation requiring interpretation in terms of such a proposed mechanism is the fact that our results show that modelocked behavior was achieved with or without an explicit polarizing element. This was done by using a polarizing Faraday optical isolator alternatively with a polarization insensitive isolator. Furthermore no other published work has exhibited such effects without a polarizing element. These considerations do not pertain to the polarization controller (in this case the 3 paddle type) since such a device alters the state, but passes all incident states of polarization without selective loss. Its function here is mainly to set the optimum value of Q. Work is presently planned to establish whether the pump laser's polarization actually provides a selection mechanism upon each successive cycle of the lasing signal beam through the ring cavity. Such a mechanism has also not been previously proposed. One approach would be to use two pump lasers (or one divided) oriented so as to combine opposite polarizations in a beam splitter prior to launching in the fiber. The cavity pumping would then fill all polarization states uniformly and be non-selective.

Various other forms of the optical Kerr effect have been used to explain passive mode- locking in both bulk solid state and fiber lasers. For example, it recently was found that Kerr self focusing can produce self mode-locking in Ti:sapphire lasers[15]. Non linear polarization rotation has been invoked as the mechanism for mode-locking in the case of some solid state lasers and recently to explain various forms of mode-locking in erbium doped fiber ring lasers[16, 6-10]. Indeed, most, if not all, fiber ring lasers described to date have utilized polarization sensitive isolators or a polarization insensitive isolator and an intercavity polarizer to provide

polarization selectivity as well as unidirectional operation. The implication is that a polarizing element is needed in the ring to permit the evolution of nonlinear polarization rotation. Our work is interesting in that no such polarizing element was used to initiate mode locking. This means either that some residual polarization in the isolator or some other element of the ring is sufficient to induce nonlinear polarization rotation, or some other mechanism is responsible for mode-locking in our laser. For example, the gain obtained in the erbium doped fiber segment of the ring is a fairly sensitive function of the match between the mode of the pump radiation and the lasing mode. It is conceivable that a non linear modulation of the fiber index akin to the Kerr self focusing effect found in Ti:sapphire lasers can optimize the mode overlap for high intensity pulses and hence promote mode locking.

It should be noted that somewhat shorter pulses were obtained when a non polarizing isolator rather than a polarizing isolator was used in our laser. The polarizing isolator was pig tailed with polarization preserving fiber which was difficult to splice onto the standard telecommunications fiber used in the rest of the ring. It is felt that the increased loss incurred because of this reduced the peak power of the pulses circulating in the ring and hence the pulse width. This implies that any reduction in loss achieved by optimizing the components used in the ring will result in a further reduction of pulse width. Reducing the fraction of the power extracted is one of the most obvious ways of reducing losses in the ring. We plan, therefore, to determine the effect of coupling ratio on mode locked pulse width.

V. Conclusions

The results shown above illustrate the extent to which a commercial erbium doped fiber gain module, designed to be used in an optical amplifier at a nominal wavelength of 1.50 µm, can be converted into a mode-locked ring laser. Except for the polarization controller, the components which form the ring cavity of the laser are simple and compact and could easily be combined with the components of the gain module (i.e. the pump laser, the WDM, and the erbium fiber) in one compact, rugged package. However, the polarization controllers generally used in fiber ring lasers are of the three paddle type and from a practical standpoint are quite cumbersome compared to the other components. They are essentially variable wave plates which provide a wide range of polarization states by introducing a controlled amount of birefringence

into a certain length of optical fiber. Our experience indicates that only a restricted range of polarization states is necessary to ensure mode locking and minimum pulse width. We are therefore investigating the possibility of reducing the size of this type of polarization controller and other more compact ways of controlling birefringence in the ring.

The pulse shortening, illustrated in Fig. 13, which resulted from the use of dispersion shifted fiber in the ring may indicate an important way of improving the performance of these simple modelocked lasers. Further reduction in the length of dispersive fiber in the ring can be achieved, and experiments in this direction are planned.

In summary, the observations to date are consistent with the proposed theoretical mechanisms, but more experimental work is required to confirm this and to determine if there are any other contributing effects not yet identified. Even at this stage, the ring laser here demonstrated entails the simplest, passive configuration with the lowest threshold to exhibit self pulsed effects. Most other configurations require additional components such as modulators and etalons. This system design is modular and shows significant progress toward the goal of a practical pulsed or CW fiber laser. One focus of future work is to establish the control required to vary the pulse width and power independently, and to incorporate amplification if required. This would facilitate a variety of communication and fiber based sensor applications.

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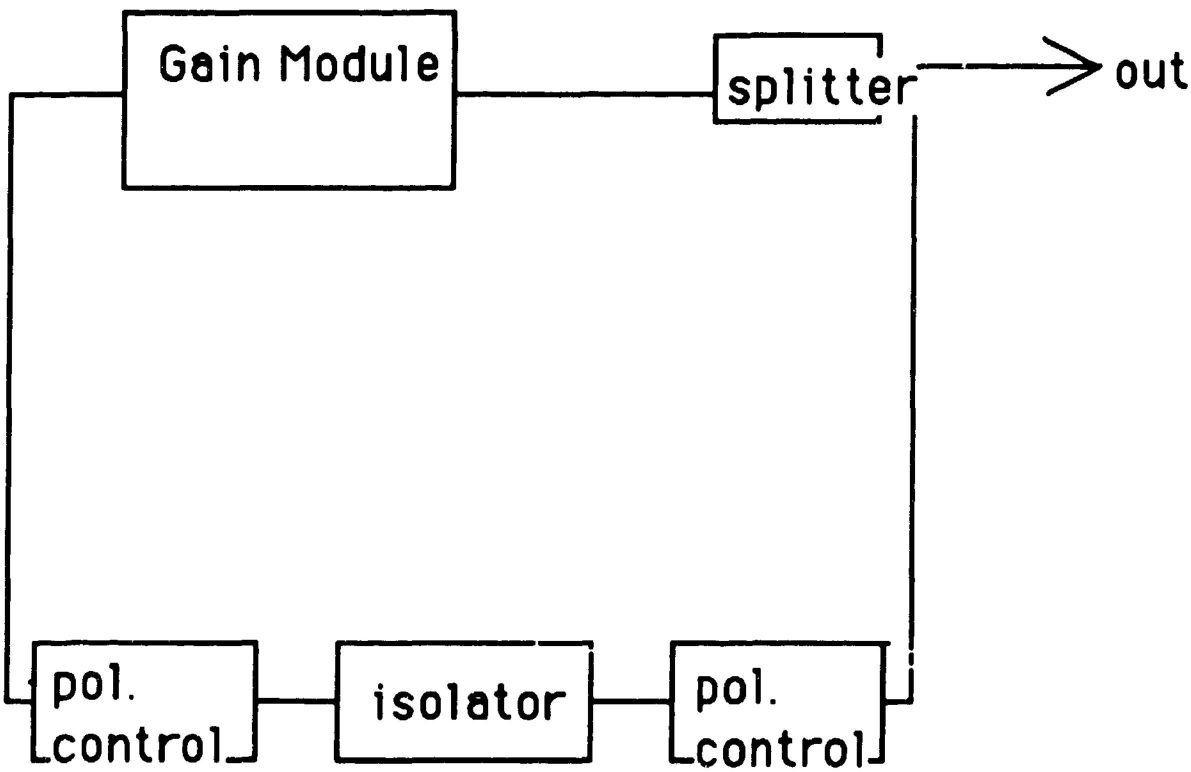


Fig.1 Experimental layout.

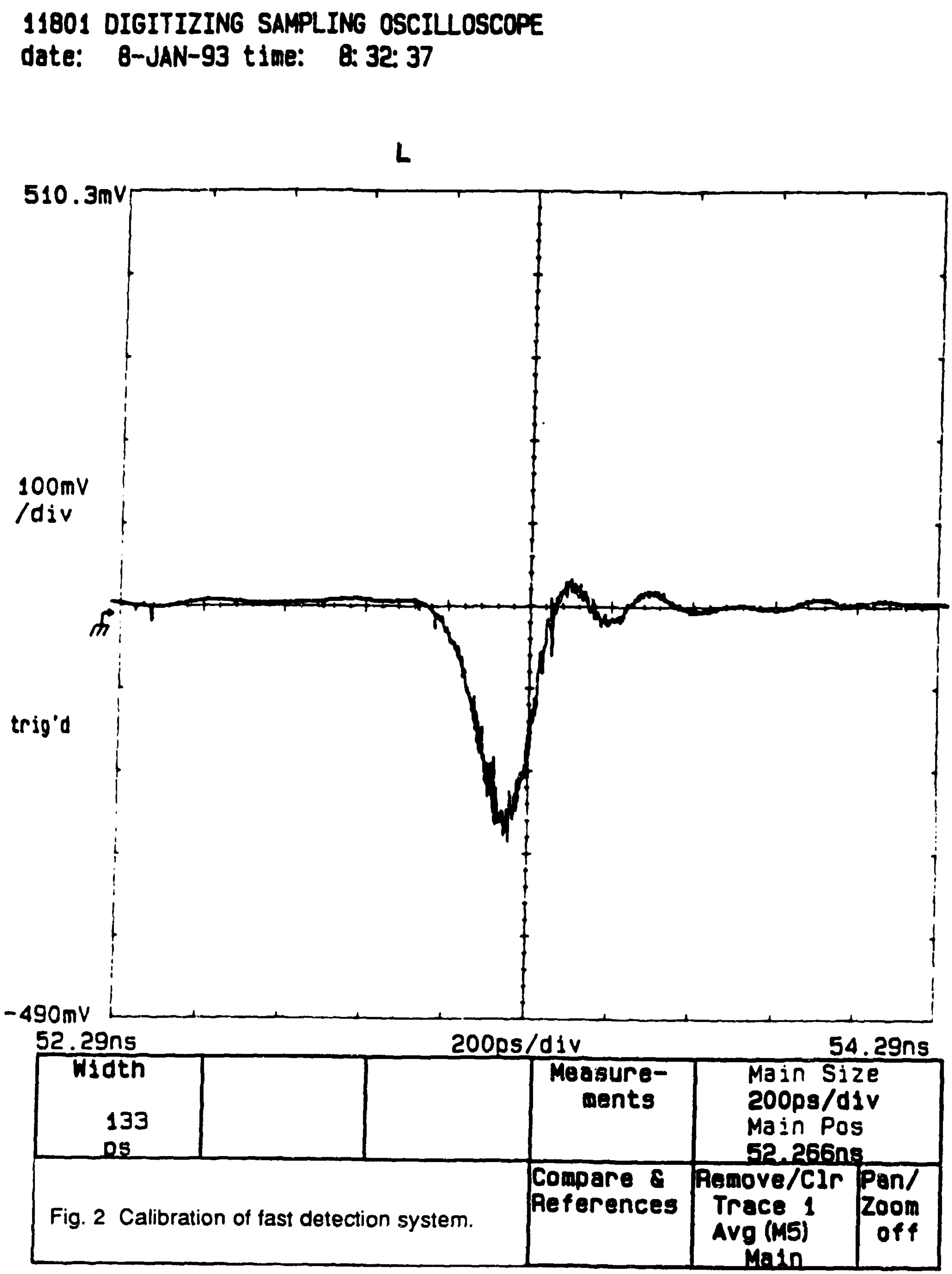


Fig. 2 Calibration of fast detection system.

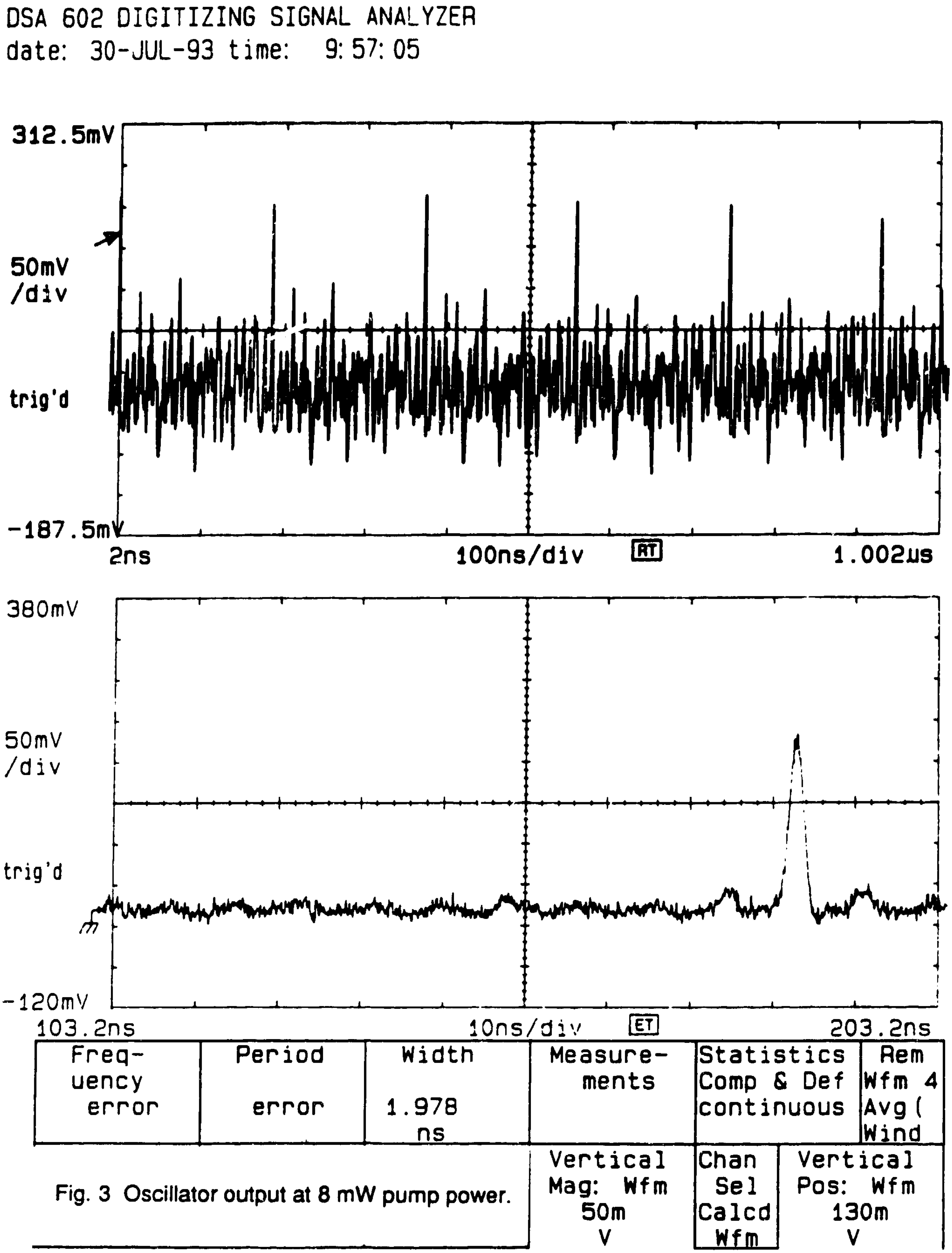


Fig. 3 Oscillator output at 8 mW pump power.

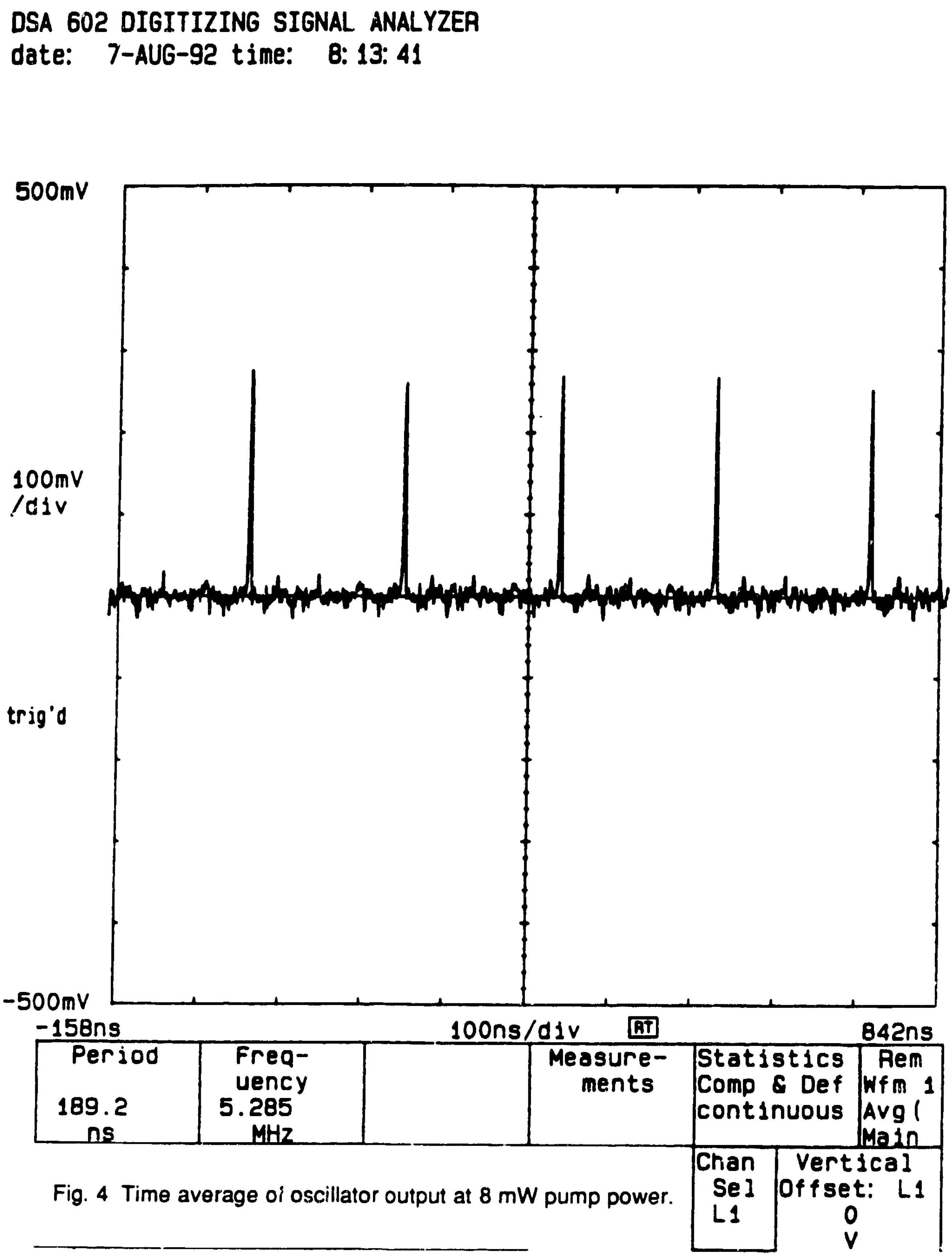
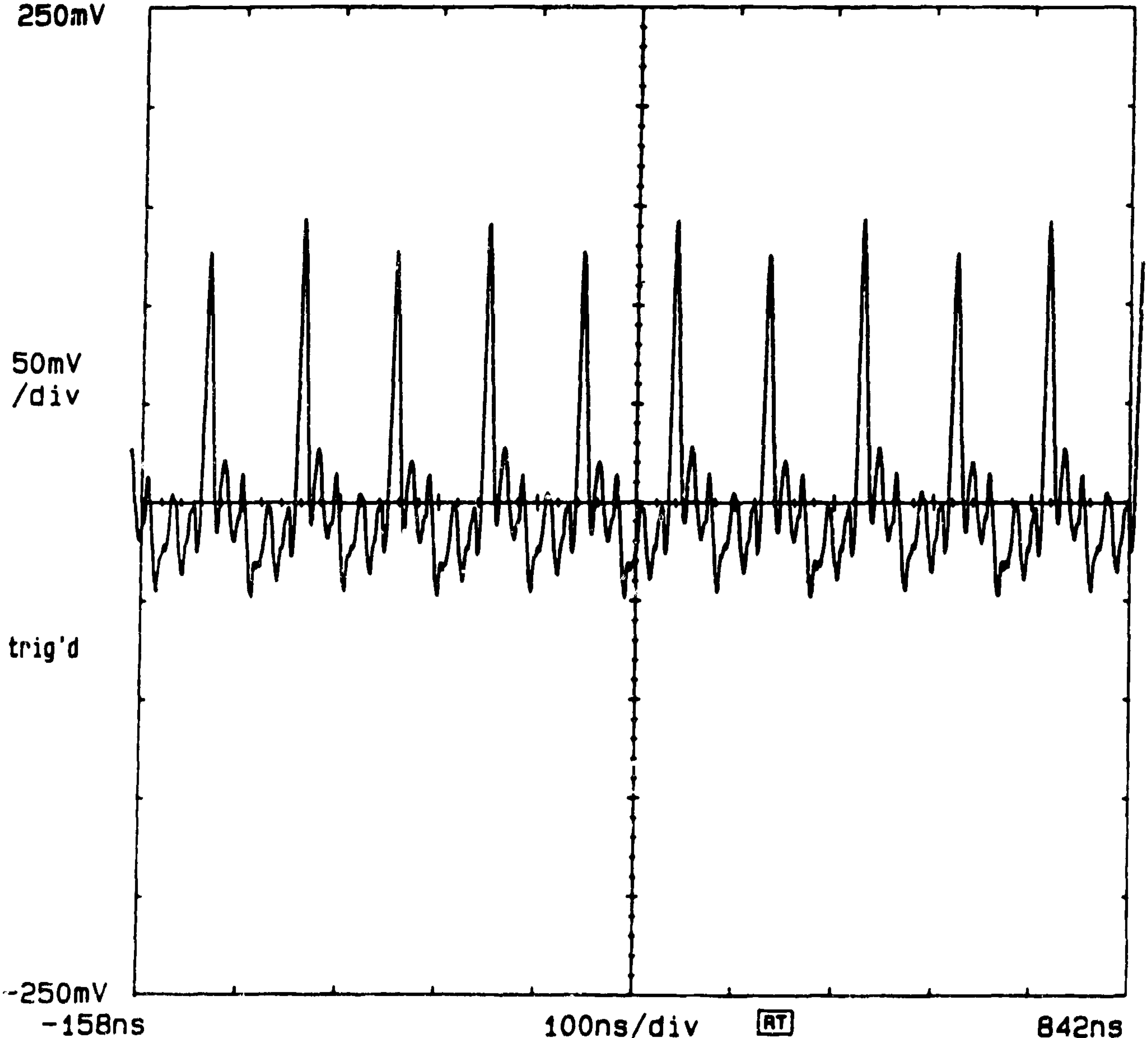


Fig. 4 Time average of oscillator output at 8 mW pump power.

DSA 602 DIGITIZING SIGNAL ANALYZER
date: 7-AUG-92 time: 7:53:15



Period	Frequency		Measurements	Statistics	Rem
94.29 ns	10.61 MHz			Comp & Def continuous	Wfm 1 Avg (Main

Pan/ Zoom	Main Position
Off	-170ns

Fig. 5 Time average of oscillator output at 20 mW pump power.

11801 DIGITIZING SAMPLING OSCILLOSCOPE
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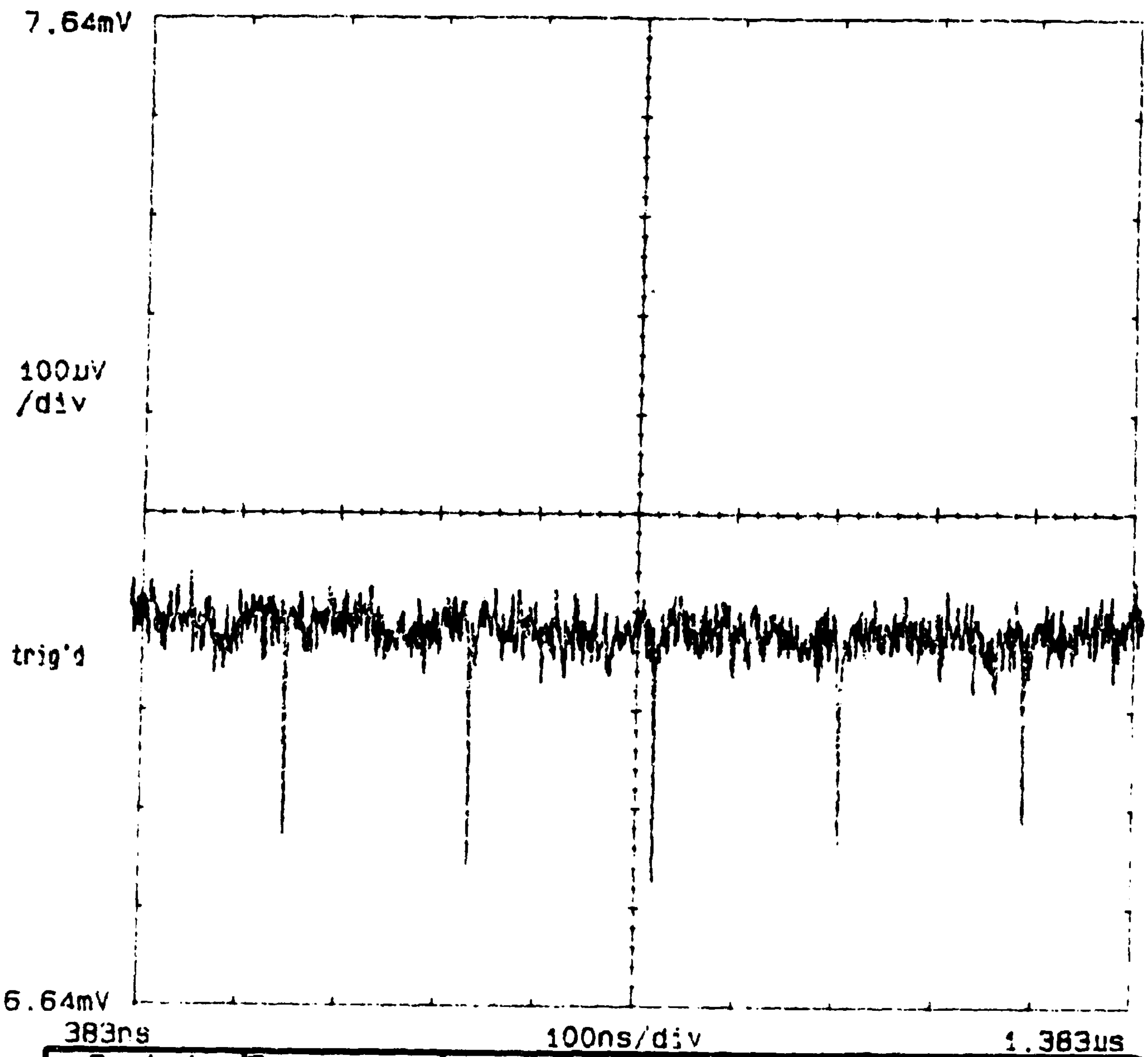

Period	Frequency	Width	Measure-ments	Vert Mag: Tra
185.959 ns	5.37752 MHz	1.246 ns		100µV/div Vert Pos: Tra 7.14mV

Compare & References	Remove/Clr Trace 1 Avg (M5) Main	Chan Sel Calcd Tra

Fig. 6 Average pulse width.

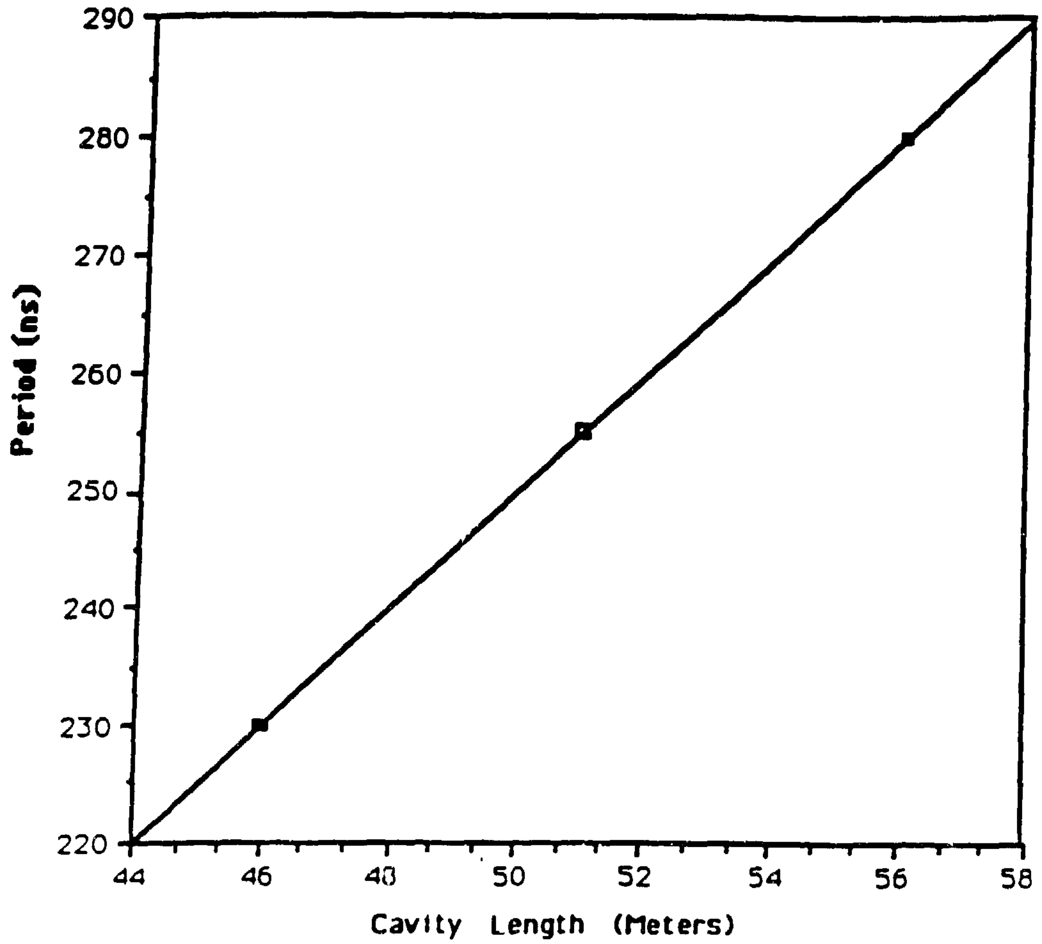

Fig. 7 Period of output pulses as a function of cavity length.

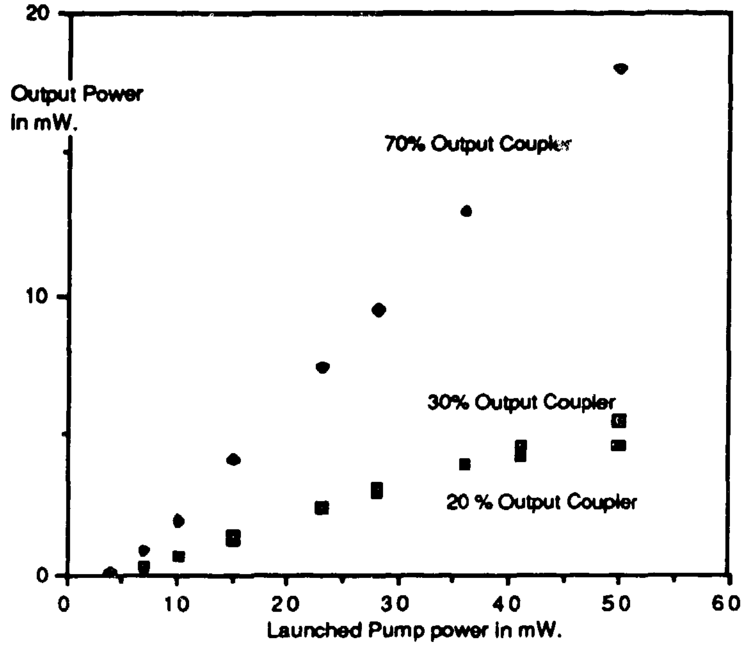

Fig. 8. Output power vs pump power

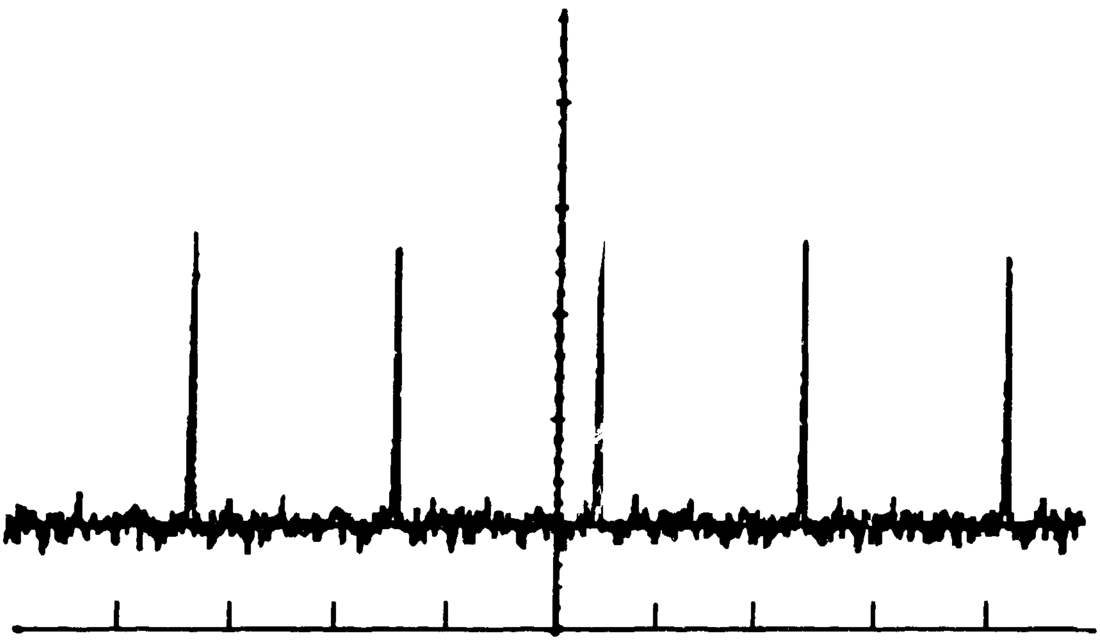

Fig. 9. Mode-locked pulse train. One division equals 50 ns. The period of the pulses was 189 ns.

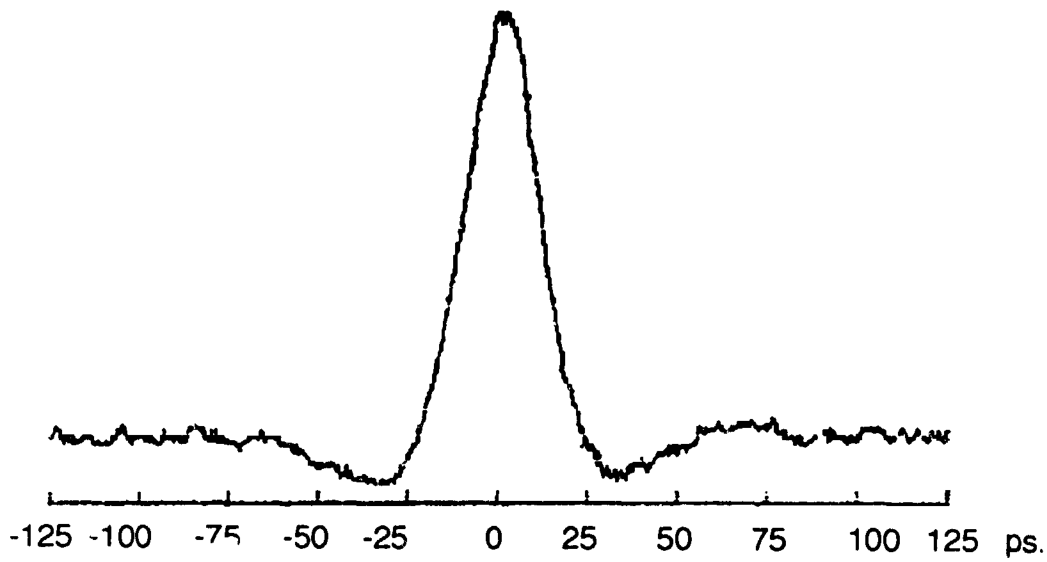

Fig.10 Autocorrelation trace of output pulses with polarizing isolator at a pump power of 50 mW.

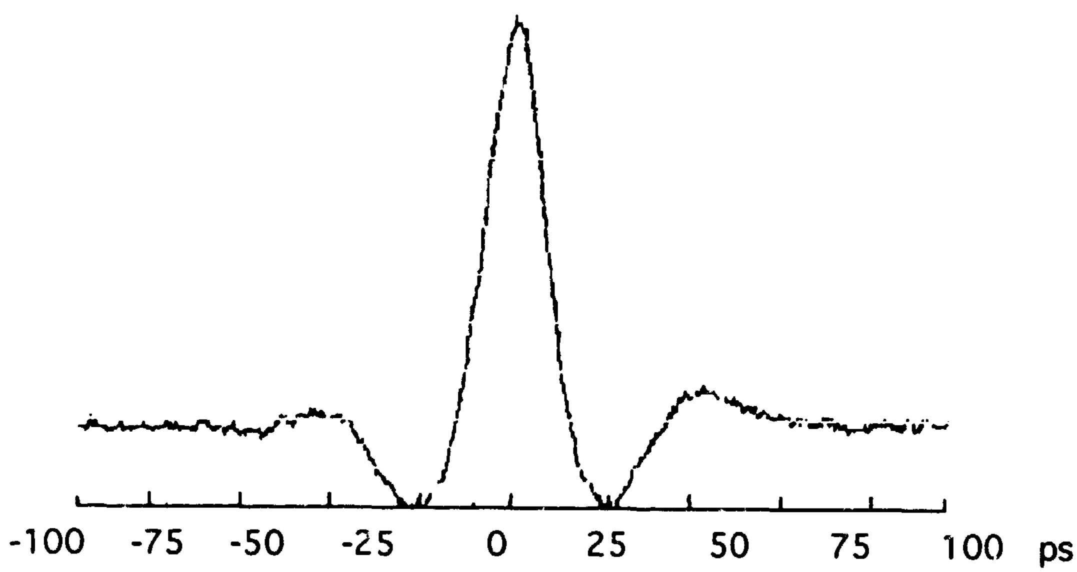

Fig 11. Autocorrelation trace with non-polarizing isolator at a pump power of 50 mW.

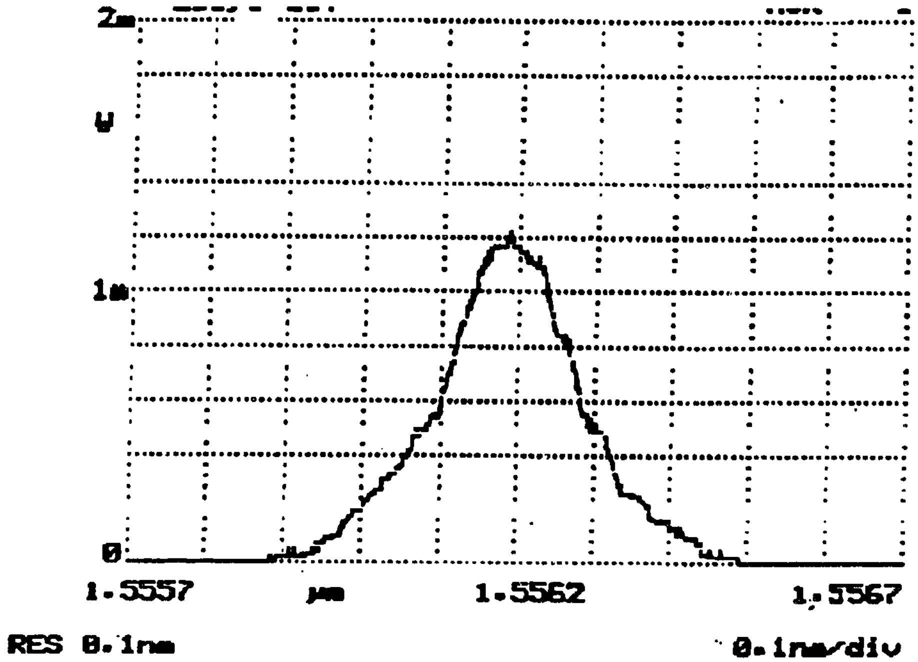

Fig. 12. Optical spectrum of pulse shown in Fig. 4

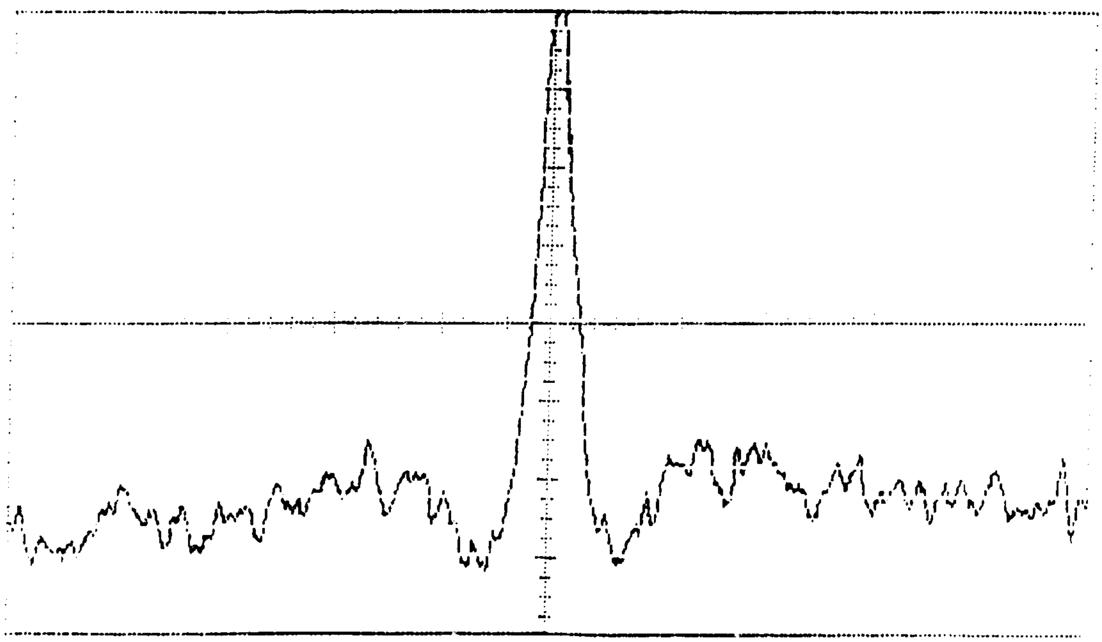

Fig. 13 Autocorrelation trace of the laser output with one paddle polarizer wound with fiber with zero dispersion at 1.55µm.

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